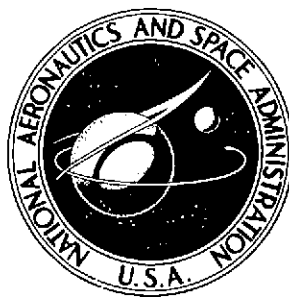


NASA TECHNICAL NOTE



NASA TN D-7787

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(NASA-TN-D-7787) FRICTION BEHAVIOR OF
304 STAINLESS STEEL OF VARYING HARDNESS
LUBRICATED WITH BENZENE AND SOME BENZYL
STRUCTURES (NASA) 14 p HC \$3.00

N74-34001

CSCL 11H H1/15

Unclas
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1. Report No. NASA TN D-7787	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle FRICION BEHAVIOR OF 304 STAINLESS STEEL OF VARYING HARDNESS LUBRICATED WITH BENZENE AND SOME BENZYL STRUCTURES		5. Report Date SEPTEMBER 1974	6. Performing Organization Code
		8. Performing Organization Report No. E-7909	
7. Author(s) Donald H. Buckley		10. Work Unit No. 502-01	11. Contract or Grant No.
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		13. Type of Report and Period Covered Technical Note	
		14. Sponsoring Agency Code	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546			
15. Supplementary Notes			
16. Abstract The lubricating properties of some benzyl and benzene structures were determined by using 304 stainless steel surfaces strained to various hardnesses. Friction coefficients and wear track widths were measured with a Bowden-Leben type friction apparatus by using a pin-on-disk specimen configuration. Results obtained indicate that benzyl monosulfide, dibenzyl disulfide, and benzyl alcohol resulted in the lowest friction coefficients for 304 stainless steel, while benzyl ether provided the least surface protection and gave the highest friction. Strain-hardening of the 304 stainless steel prior to sliding resulted in reduced friction in dry sliding. With benzyl monosulfide, dibenzyl disulfide, and benzyl alcohol changes in 304 stainless steel hardness had no effect upon friction behavior.			
17. Key Words (Suggested by Author(s)) Friction; Benzyl structures; Friction of 304 stainless steel; Hardness; Lubrication; Benzene		18. Distribution Statement Unclassified - unlimited Category 15	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 13	22. Price* \$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FRICTION BEHAVIOR OF 304 STAINLESS STEEL OF VARYING HARDNESS LUBRICATED WITH BENZENE AND SOME BENZYL STRUCTURES

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SUMMARY

An investigation was conducted to determine the effectiveness of various benzene and benzyl compounds in the lubrication of 304 stainless steel strain-hardened to various hardnesses. The lubricants examined included benzene, benzyl monosulfide, and dibenzyl disulfide; nitrobenzene, benzyl formate, benzyl alcohol, and benzyl amine. The 304 stainless steel ranged in Rockwell hardness from C-16 to C-52. The friction experiments were conducted on a Bowden-Leben type apparatus. Experimental parameters included a sliding velocity of 0.15 centimeter per minute, loads from 50 to 300 grams, and room temperature.

Of the benzene and benzyl compounds examined in this study benzyl monosulfide, dibenzyl disulfide, and benzyl alcohol gave the lowest friction coefficients for 304 stainless steel, while benzyl ether gave the highest. Strain-hardening of the 304 stainless steel prior to sliding resulted in reduced friction for the unlubricated surface. Strain-hardening had no effect, however, on the friction characteristics of 304 stainless steel lubricated with benzyl monosulfide, dibenzyl disulfide, or benzyl alcohol. The materials used had such good lubricating characteristics that the effect of hardness was completely masked.

INTRODUCTION

The 300 series stainless steels, in particular 304 stainless steel, are used by design engineers in lubrication system components. One of the most common applications of 304 stainless steel to lubrication systems is use in mechanical gears. The selection of 304 stainless steel is made on the basis of mechanical strength considerations, but it is one of the poorest possible materials for such use with respect to adhesion, friction, and wear. Further, this particular material is one of the most difficult to lubricate.

Most straight conventional lubricating oils are not adequate lubricants for gear applications. Additives, therefore, are most frequently blended with the basic lubricating oils in order to ensure adequate lubrication under the heavy loading encountered with gears. These materials are generally aliphatic or aromatic compounds containing active atoms in the molecule such as sulfur, phosphorus, or chlorine or an acid. A typical additive is dibenzyl disulfide.

During actual contact in gears the metal can and frequently does undergo strain-hardening. This straining in the presence of lubricant additives raises two questions: first, does the strain-hardening affect chemical reactivity of the lubricant additive with the metal surface, and second, if it does, how does this effect influence friction and wear.

The objectives of this investigation were (1) to examine various aromatic structures as lubricants for 304 stainless steel and (2) to determine the influence of strain-hardening in 304 stainless steel on the friction behavior in the presence of the aromatic structures as determined by friction coefficient. Friction experiments were conducted in a simple Bowden-Leben type friction apparatus by using a pin-on-disk specimen configuration. Various benzene and benzyl structures were examined. These included benzene, nitrobenzene, benzyl formate, benzyl ether, benzyl alcohol, benzyl amine, benzyl monosulfide, and dibenzyl disulfide. In addition to 304 stainless steel sliding on itself, both aluminum and copper riders (pins) were made to slide on 304 stainless steel.

APPARATUS AND MATERIALS

The apparatus used in this investigation is shown schematically in figure 1. The apparatus consisted basically of a scratch hardness tester to which a drive motor was attached in order to provide uniform motion of the specimens under examination. The drive motor, through a gear assembly, moved the lower specimen from right to left at a constant speed of 0.15 centimeter per minute.

The pin specimen was 304 stainless steel, aluminum, or copper 3.0 millimeters in diameter. The arm containing the pin had a strain-gage assembly for measuring frictional force. The output was recorded on a strip-chart recorder. The pin was loaded against the 304 stainless steel surface by the application of dead weights directly over the rider. The load range was 50 to 300 grams.

The 304 stainless steel used in this investigation was a commercial grade material and was not given any special treatment; however, all the specimens were taken from the same sheet of steel. The aluminum and copper riders used were of 99.999-percent-pure metals.

The benzene was 99 percent pure and thiophene free. It was given no special treatment prior to use. All the other aromatic benzene and benzyl structures used were reagent grade materials. The materials and their structures are presented in table I.

PROCEDURE

Alloy Preparation

The 304 stainless steel, copper, and aluminum specimens were initially completely annealed in a vacuum furnace. Specimens were polished on metallurgical paper to 600 grit. The 304 stainless steel and aluminum surfaces were then electropolished in a solution of 12 percent perchloric acid in ethyl alcohol. The copper was electropolished in phosphoric acid.

Strain-Hardening

Strain-hardening was produced in the specimens by pressing them in a hydraulic press at pressures to 1474 newtons per square millimeter. The resulting Rockwell hardnesses for 304 stainless steel varied from C-16 for the annealed specimens to C-52 for the fully strained specimens. The 304 stainless steel flats were pressed between two cool, flat, smooth steel dies. Specimen sample dimensions were 2.5 by 2.5 centimeters for Rockwell hardnesses to C-35 and were 1.25 by 2.5 centimeters for hardnesses greater than C-35.

Deposition of Films

Each metal sample was placed in a quartz tube which was evacuated to a pressure of 10^{-3} torr. The sample was heated to 300°C to remove adsorbed surface films such as water vapor. The specimen was then cooled to room temperature, and the lubricant was admitted to the evacuated system. It condensed on the specimen. The specimen was then removed from the tube and placed in the friction apparatus.

Friction Experiments

The friction experiments consisted of a single pass of the pin across the surface except where otherwise noted. The pins were all used in the initially annealed state.

Thus, they strain-hardened during sliding. Friction force was continuously measured, and the friction coefficients presented in this report represent equilibrium averages. The width of the wear scar was measured microscopically upon completion of the sliding experiments.

RESULTS AND DISCUSSION

Effect of Strain

Specimens of 304 stainless steel were strained to various hardnesses in a hydraulic press. The friction coefficient for these specimens of varying hardness was measured in laboratory air with the specimens unlubricated; the results obtained are presented in figure 2. The coefficient of friction decreased with an increase in specimen hardness. The lowest friction coefficient was obtained when the hardness was at a maximum of C-52.

The data of figure 2 reflect a trend opposite to that observed for elemental iron sliding on itself in the study of reference 1. The deformation characteristics of elemental iron are not the same as those for an alloy such as 304 stainless steel. Further, the mechanism of strain-hardening is not the same for the two materials. There are structural, composition, strain-hardening, and impurity differences in the two materials which can account for the observed differences.

Sulfur-Containing Lubricants

Thin films of benzyl monosulfide and dibenzyl disulfide were applied to the surface of 304 stainless steel specimens of varying hardness, and the friction characteristics were measured. Friction coefficients are plotted as a function of hardness of the 304 stainless steel in figure 3. Unlike the case of dry sliding, hardness had no effect upon friction behavior in the presence of benzyl monosulfide and dibenzyl disulfide. The friction coefficient was about 0.1 at all hardnesses. These results indicate that benzyl monosulfide and dibenzyl disulfide lubricate effectively enough to mask any strain-hardening effects such as those shown in figure 2.

The beneficial lubricating effects of both benzyl monosulfide and dibenzyl disulfide have been fairly well established (refs. 2 to 4). Most of the experimental research with these compounds has been with conventional bearing steels rather than stainless steels.

Benzyl monosulfide contains one sulfur atom between two benzyl structures, as indicated in the structure shown in table I. Dibenzyl disulfide is a similar structure but contains two sulfur atoms bonded to each other. The sulfur-to-sulfur bond is relatively

weak, and the compound should, therefore, be more surface active than benzyl monosulfide.

After completion of the sliding friction experiments with dibenzyl disulfide on 304 stainless steel specimens of various hardnesses, the width of the wear track on the surfaces was measured; the results obtained are presented in figure 4. There was a decrease in track width with an increase in hardness. While a decrease in track width was observed for dry sliding, the slope of the curve was not as steep as that shown in figure 4 for lubricated sliding. Thus, some decrease in track width is a direct result of a change in hardness, while some is a result of an increase in surface activity of the highly strain-hardened surfaces.

Aluminum and Copper in Contact With Stainless Steel

The data of figures 3 and 4 are for 304 stainless steel sliding on itself. In practical lubrication systems other metals such as copper and aluminum are frequently in contact with 304 stainless steel, so the behavior of these metals in contact with 304 stainless steel is of interest. Sliding friction experiments were therefore conducted with aluminum and copper contacting 304 stainless steel and lubricated with both benzyl monosulfide and dibenzyl disulfide. The results obtained are presented in figure 5.

Examination of figure 5 indicates that variations in the hardness of the 304 stainless steel do not affect friction behavior. The coefficient of friction was approximately 0.1 at all hardnesses of the 304 stainless steel. Further, the pin material did not make a difference in observed friction results. In fact, the friction coefficients with aluminum and copper riders were comparable to those obtained with 304 stainless steel pins (fig. 3). Since the friction coefficients were essentially the same for the three rider materials, it is reasonable to assume that the films formed on the stainless steel flats were responsible for the observed friction results.

Ethers as Lubricants

The aromatic ethers have been and are being considered for use as high-temperature lubricants because of their good thermal stability (refs. 5 and 6). That same good stability may render them less than ideal lubricants. To explore this concept, some sliding friction experiments were conducted with benzyl ether and benzyl alcohol lubricating 304 stainless steel. Benzyl alcohol, as indicated in table I, is a benzyl structure with a hydrogen atom in place of the second benzyl group of the benzyl ether.

The friction results obtained with these two benzyl compounds are presented in figure 6. The friction data of figure 6 indicate that the alcohol is a better lubricant than

the ether. As was observed with the sulfide, hardness does not appear to influence friction results with benzyl alcohol. The friction coefficient was 0.1 at all hardnesses, a value comparable to that obtained with the sulfide. With the ether friction was higher for the 304 stainless steel in the annealed state.

In order to gain a better insight into the friction behavior with the ether and the stainless steel in the annealed state, sliding friction experiments were conducted with benzyl ether lubricating 304 stainless steel at various loads. Friction results were also obtained with benzene for comparative purposes. The results obtained with these two fluids are presented together with that for unlubricated sliding in figure 7. Note that the friction scale on the ordinate has been compressed from that used in the earlier figures.

With benzyl ether in figure 7 the friction coefficient at a 50-gram load was extremely high (1.0). It was twice the value obtained for unlubricated sliding. The effect of increasing the load can be seen in the data of figure 7. The friction coefficient continued to decrease with increasing load until it reached a value just in excess of 0.2 at a 250-gram load.

The data of figure 7 for benzene indicate that benzene affords the 304 stainless steel better surface protection than benzyl ether at all loads. Benzene is a poor boundary lubricant, and benzyl ether appears to be even less effective. If only friction is considered, at loads of less than 150 grams it is better to run the surface dry than to use benzyl ether.

Nitrobenzene and Benzyl Amine as Lubricants

When benzyl alcohol was used to lubricate 304 stainless steel of varying hardness, the friction coefficient was 0.1 at all hardnesses (fig. 6). Sliding friction experiments were conducted with benzyl alcohol and benzyl formate at various loads, and the results are presented in figure 8. Benzyl formate is shown structurally in table I. Data for an unlubricated surface are included in figure 8 for reference purposes.

The friction coefficient with benzyl alcohol was less at all loads than that obtained with benzyl formate, which indicated that the alcohol has better lubricating characteristics than the formate. Benzyl formate was not much better in reducing friction than was benzene (fig. 7).

Lubricant additives include nitrogen compounds such as carbamates (ref. 7). In order to gain some insight into the effectiveness of nitrogen in nitrogen-containing benzyl derivatives in reducing the friction of 304 stainless steel, friction experiments were conducted with nitrobenzene and benzyl amine. The results obtained are presented in figure 9. The 304 stainless steel was completely annealed.

Figure 9 shows that at the lighter loads the friction coefficients were higher with both nitrogen compounds than those observed with benzyl alcohol (fig. 8). At loads greater than 50 grams the friction coefficient with nitrobenzene was less than that observed with benzyl amine.

Friction data presented in figure 3 for benzyl monosulfide and dibenzyl disulfide lubricating 304 stainless steel show the effect of varying hardness. The effect of load on the friction characteristics of a completely annealed sample was also determined with these compounds. As shown in figure 10, increasing the load during sliding increased the amount of strain-hardening. There was a linear decrease in friction with an increase in load for both compounds.

Figure 3 indicates that the friction coefficient for 304 stainless steel was unaffected by changes in hardness in the presence of the sulfide additives. The effect of load shown in figure 10 was therefore producing other effects than simple strain-hardening. Increasing the load would also increase the interfacial surface temperature and therefore the chemical activity of the surface (ref. 8). Increased chemical activity would mean more sulfide film to afford greater surface protection and less metal-to-metal adhesion. This may account for the results of figure 10.

All the data reported thus far were the result of a single rider pass across an annealed 304 stainless steel flat. Some interesting observations were made with copper sliding on 304 stainless steel in air (30 percent relative humidity) and with the surface lubricated with dibenzyl disulfide and subjected to repeated passes of the rider. The results obtained are presented in figure 11.

In air the friction increased in the first four passes. After the fourth pass the friction remained unchanged. The increase reflected an increase in metal-to-metal contact through the absorbed surface layers and oxides. The friction coefficient did not exceed 0.2 because the experiments were conducted in ordinary laboratory air containing moisture. With dibenzyl disulfide the friction coefficient remained relatively unchanged with repeated passes over the same surface, which indicated that the lubricating film was developed in the first pass across the surface.

SUMMARY OF RESULTS

The following results were obtained in an investigation of the friction behavior of 304 stainless steel strain-hardened to various degrees and lubricated with benzene and benzyl type compounds:

1. Of the benzyl and benzene compounds examined in this investigation, benzyl monosulfide, dibenzyl disulfide, and benzyl alcohol provided the lowest friction coefficient for 304 stainless steel.
2. Benzyl ether was a very poor lubricant for the stainless steel.

3. With benzyl monosulfide, dibenzyl disulfide, and benzyl alcohol changes in 304 stainless steel hardness had no effect upon friction behavior.

4. Increasing the hardness of 304 stainless steel with dry sliding resulted in a decrease in friction. The higher the hardness, the lower the friction.

5. Some benzyl compounds were sensitive in their friction coefficients to load, while others were not. Benzyl ether had the greatest sensitivity to changes in load.



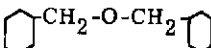
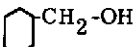
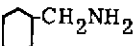
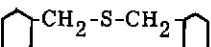
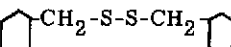
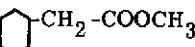
6. When copper or aluminum pins were used in contact with stainless steel flats, the friction results obtained were the same as those observed for stainless steel in contact with itself.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 25, 1974,
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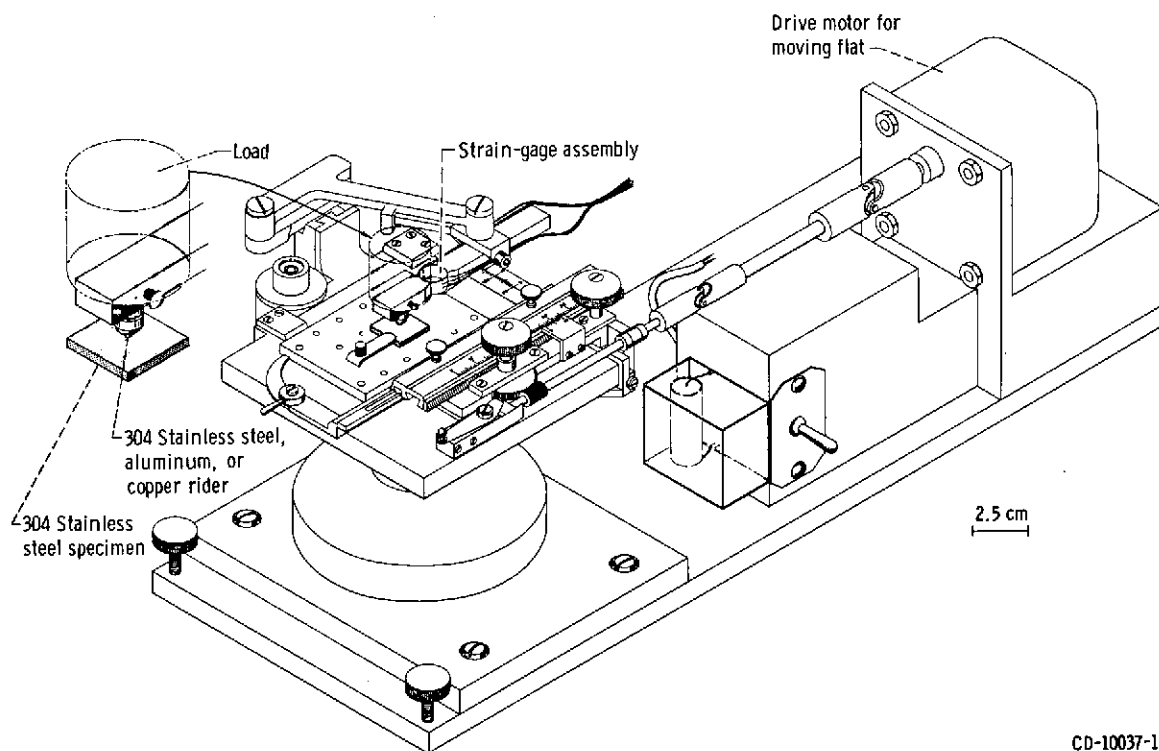
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TABLE I. - LUBRICANTS USED AS FILMS

Common chemical name	Formula (a)	State	Boiling point (bp) or melting point (mp), °C
Benzene		Liquid	bp, 205
Nitrobenzene		Liquid	bp, 211
Benzyl ether		Liquid	bp, 295
Benzyl alcohol		Liquid	bp, 205
Benzyl amine		Liquid	bp, 185
Benzyl monosulfide		Solid	mp, 49
Dibenzyl disulfide		Solid	mp, 70
Benzyl formate		Liquid	bp, 203

^aNitrogen, N; oxygen, O; carbon, C; hydrogen, H; sulfur, S.



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Figure 1. - Sliding friction apparatus..

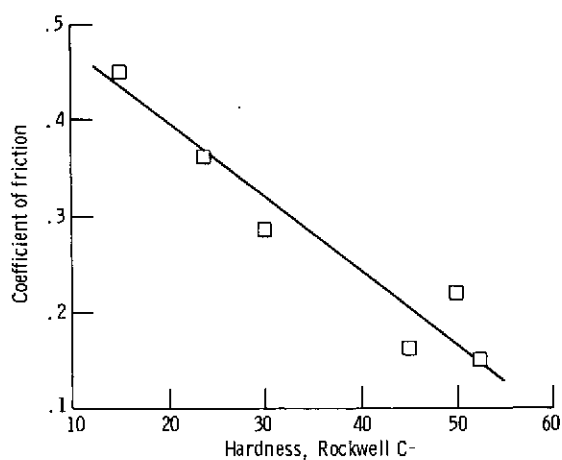


Figure 2. - Coefficient of friction as function of hardness for unlubricated 304 stainless steel sliding on 304 stainless steel in laboratory air. Sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23° C.

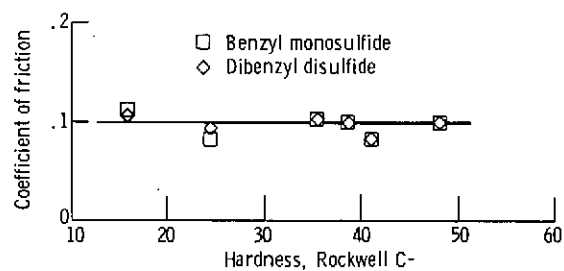


Figure 3. - Coefficient of friction as function of hardness for 304 stainless steel sliding on 304 stainless steel. Lubricants, benzyl monosulfide and dibenzyl disulfide; sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23° C.

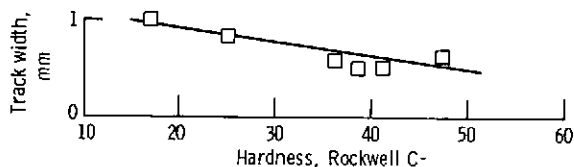


Figure 4. - Track width for single pass of 304 stainless steel rider over 304 stainless steel disk. Lubricant, dibenzyl disulfide; sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23° C.

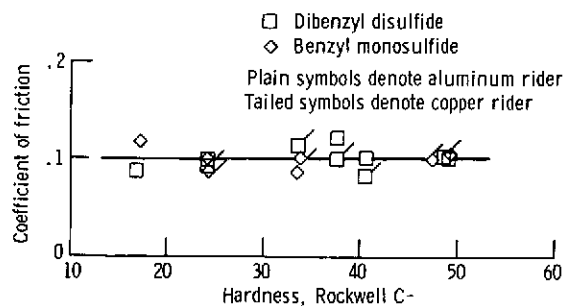


Figure 5. - Coefficient of friction as function of hardness for aluminum and copper sliding on 304 stainless steel. Sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23° C.

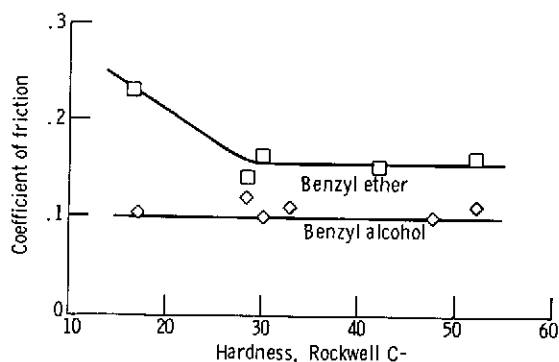


Figure 6. - Coefficient of friction as function of hardness for 304 stainless steel sliding on 304 stainless steel. Lubricants, benzyl ether and benzyl alcohol; sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23° C.

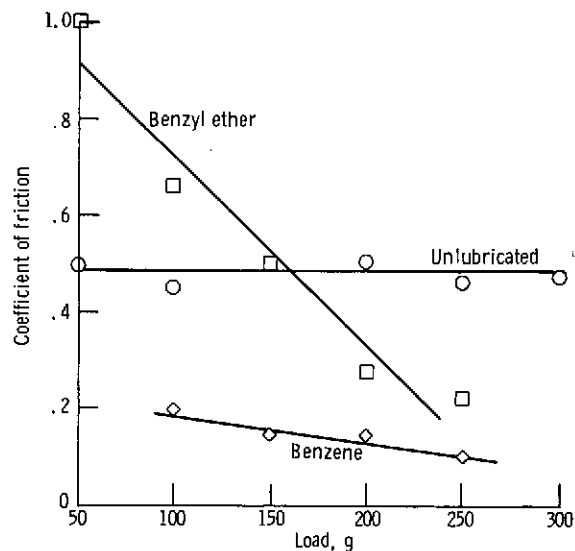


Figure 7. - Coefficient of friction as function of load for 304 stainless steel sliding on 304 stainless steel unlubricated and with benzyl ether and benzene films. Sliding velocity, 0.15 centimeter per minute; temperature, 23° C; stainless steel annealed to Rockwell hardness of C-16.

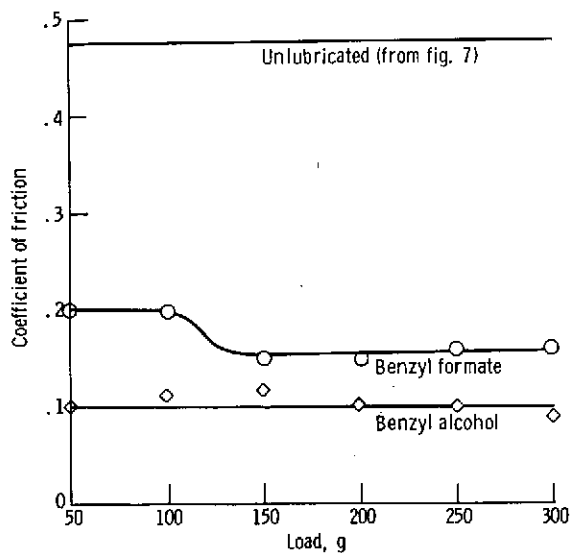


Figure 8. - Coefficient of friction as function of load for 304 stainless steel sliding on 304 stainless steel unlubricated and with benzyl alcohol and benzyl formate films. Sliding velocity, 0.15 centimeter per minute; temperature, 23° C; stainless steel annealed to Rockwell hardness of C-16.

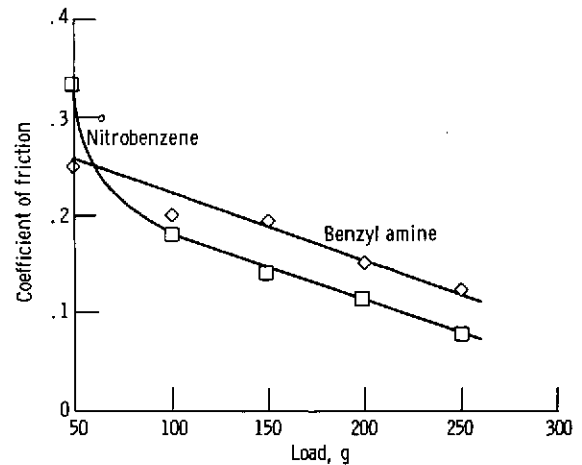


Figure 9. - Coefficient of friction as function of load for 304 stainless steel sliding on 304 stainless steel with two nitrogen-containing films. Sliding velocity, 0.15 centimeter per minute; temperature, 23° C; stainless steel annealed to Rockwell hardness of C-16.

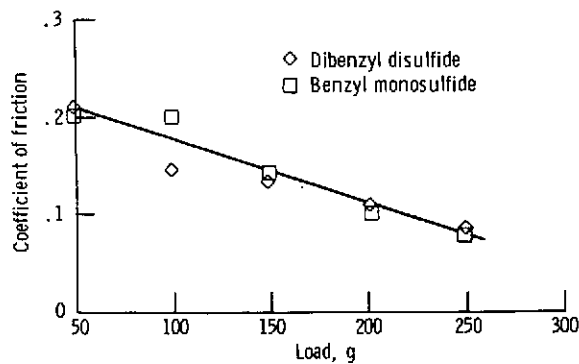


Figure 10. - Coefficient of friction as function of load for 304 stainless steel sliding on 304 stainless steel with benzyl monosulfide and dibenzyl disulfide films. Sliding velocity, 0.15 centimeter per minute; temperature, 23° C; stainless steel annealed to Rockwell hardness of C-16; width of tracks, 1.0 millimeter.

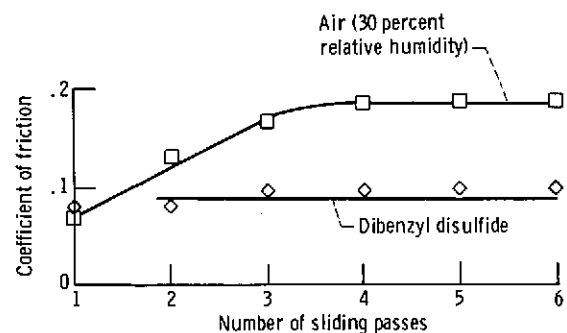


Figure 11. - Coefficient of friction as function of number of passes for copper sliding on annealed 304 stainless steel. Sliding velocity, 0.15 centimeter per minute; load, 200 grams; temperature, 23° C.